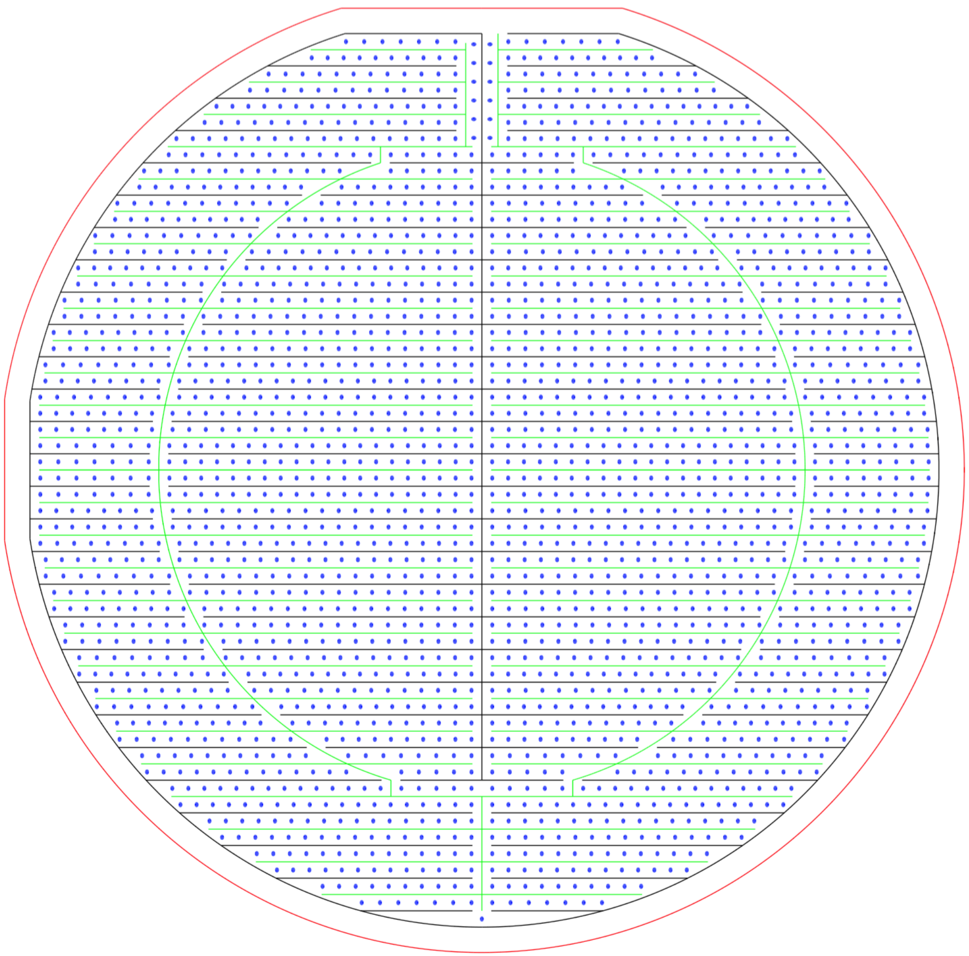
A Phased Approach to Building Extremely Senstive Calorimeters for Photons and Rotons

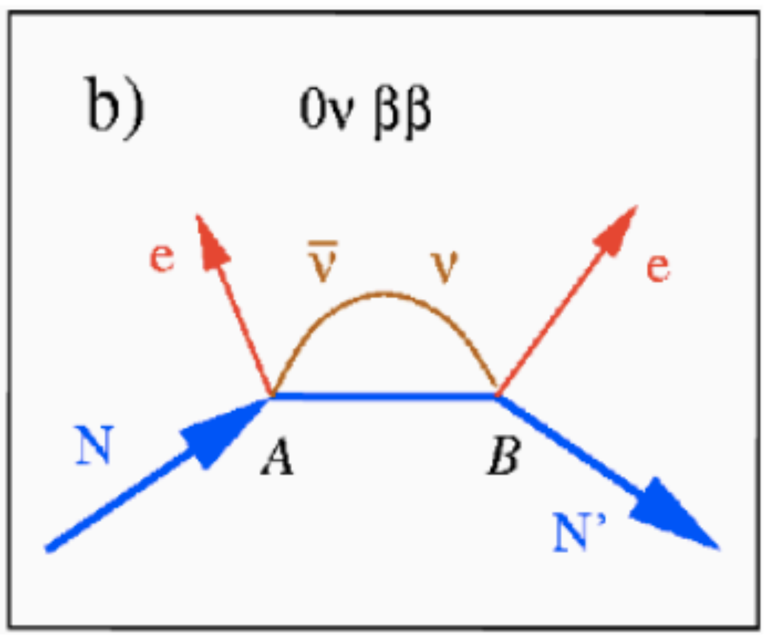


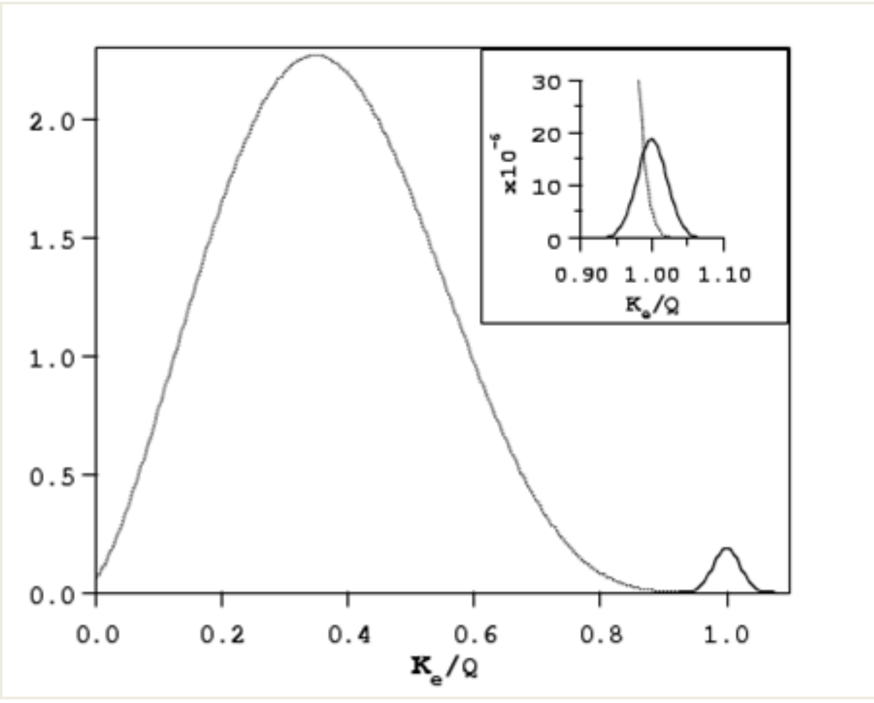
Matt Pyle
(for Many People)
Sub-eV @ LBL
12/07/16

Science needs very sensitive large area cryogenic photon and roton detectors

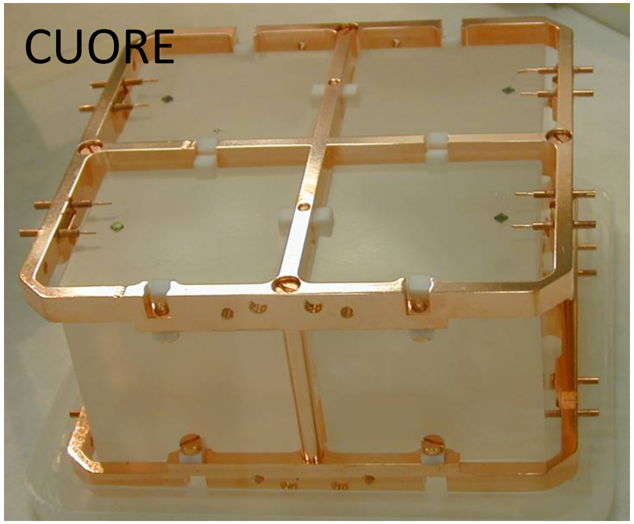
1) Neutrinoless Double Beta Decay

- Most sensitive test of
  - lepton number conservation
  - Majorana/Dirac nature of ν
- Central to most theories of Leptogenesis
- Potentially measures ν mass



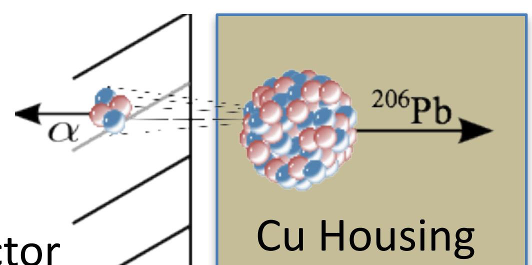


0νDBD: Cryogenic Calorimeters

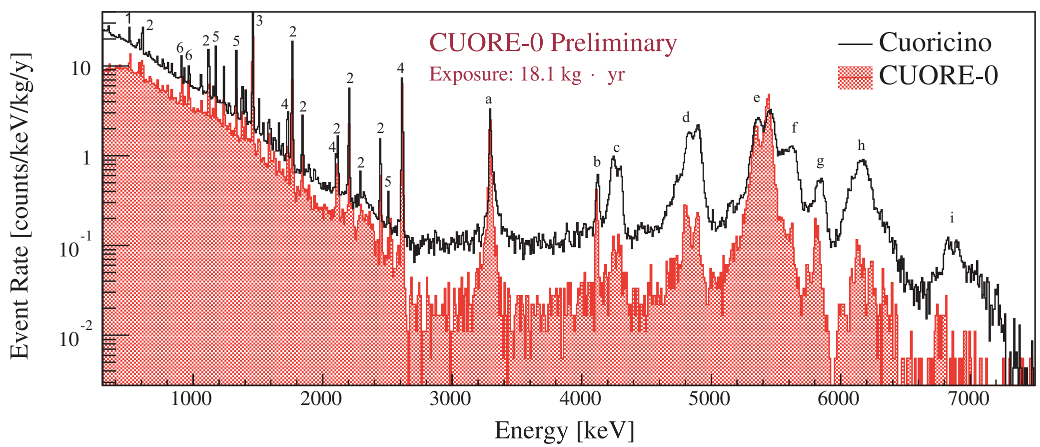


- Advantages:
  - Excellent energy resolution
  - Variety of target isotopes

- Disadvantage: Backgrounds, in particular degraded alphas from Cu support structure



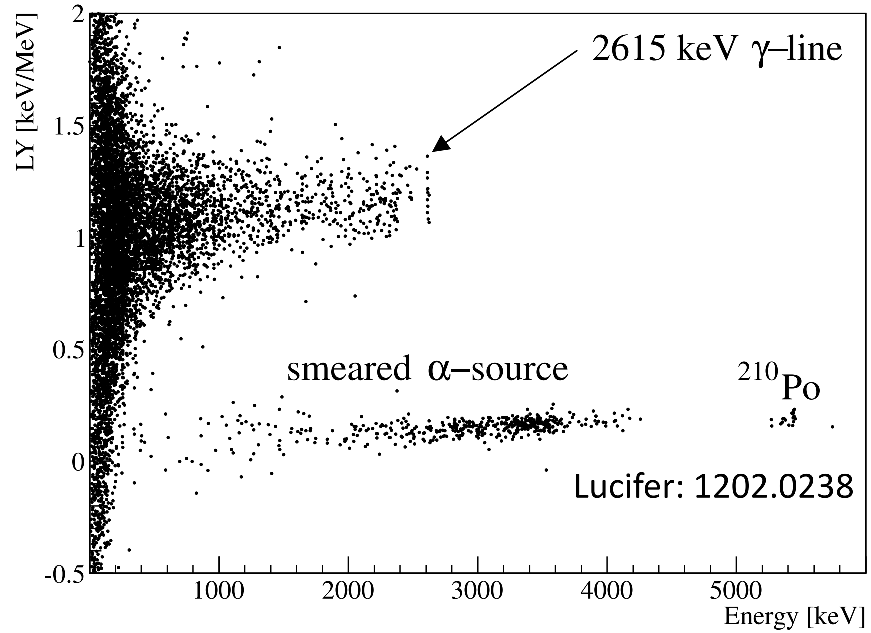
CUORE-0: AIP Conf Proc 1666, 170001 (2015)

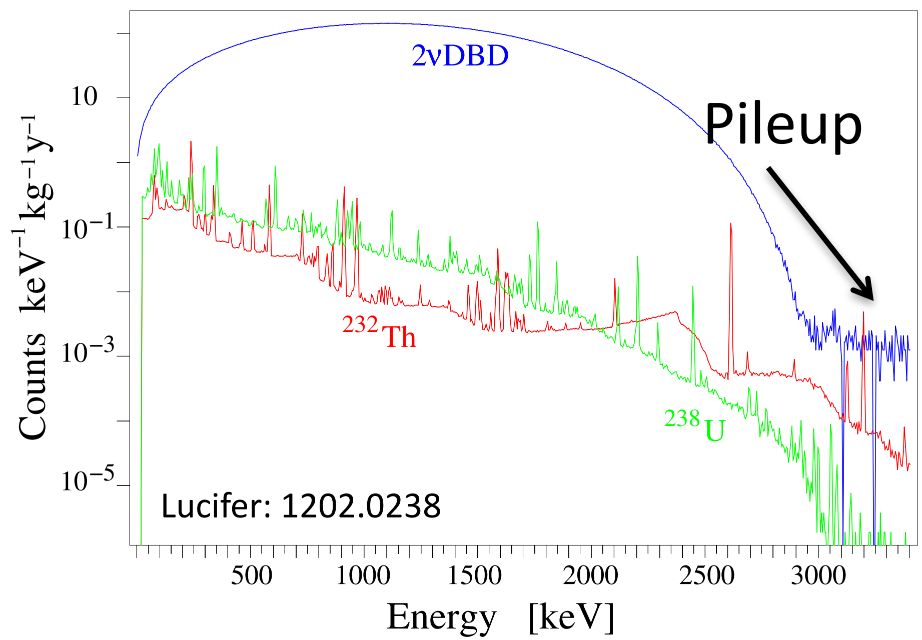


0νDBD: Cryogenic Calorimeters & Photon Detectors

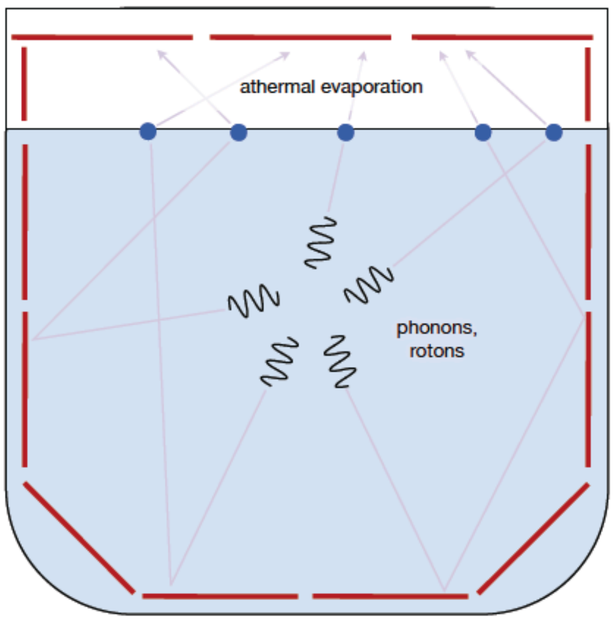
Large area, High QE Photon Detector:

- TeO_2:100 eV Cherenkov light for ββ event:
  - 10 eV Sensitivity
- $ZnMoO_4$:3 keV Scintillation light for ββ events
  - 30 eV Sensitivity
  - Fast (1us) sensor response to minimize pileup



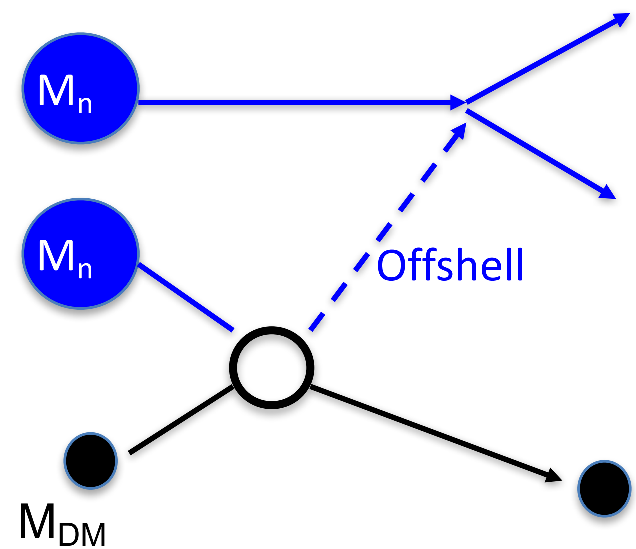


2) Superfluid He Dark Matter Detector

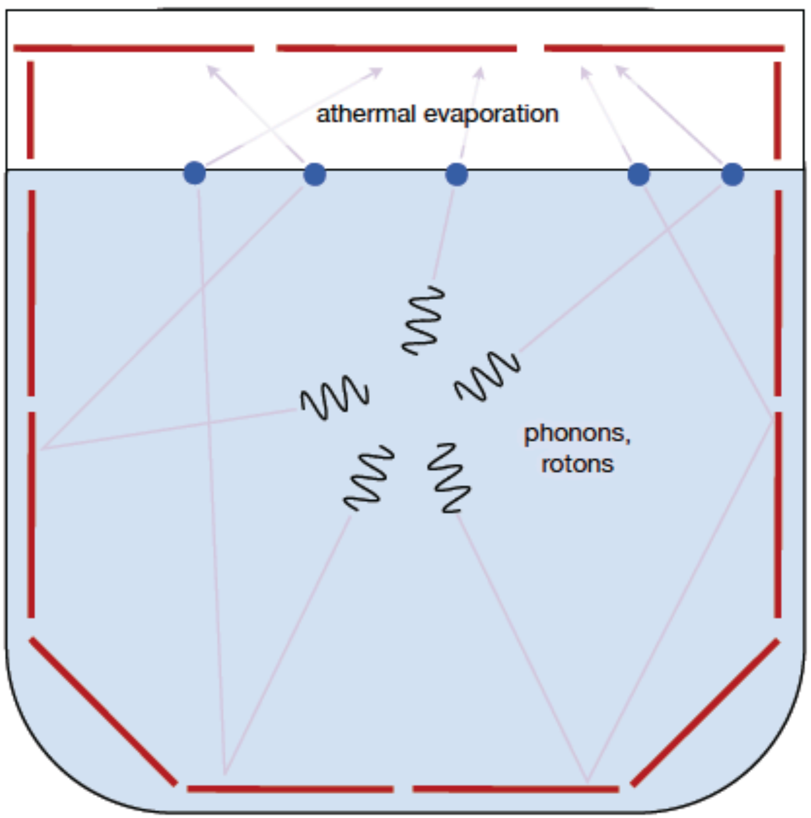


- Superfluid He: Many Long Lived Excitations
  - Photons & Triplet Excimers: ~ 18 eV
  - Phonons & Rotons: 1 meV
  - x10 gain due to adsorption on bare surface
- D. McKinsey et al (1302:0534)

- Simple elastic NR scattering just doesn't give you a measureable recoil
- Use off-shell processes that produce 2 back to back offshell phonons
- Schutz and Zurek: 1604.08206



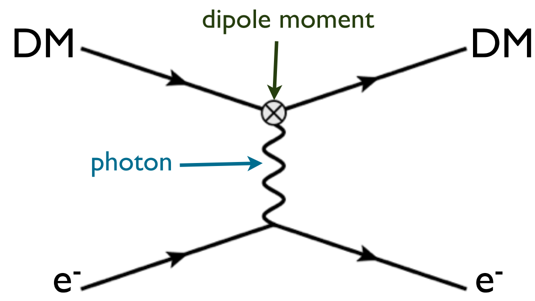
Superfluid He Detector Needs

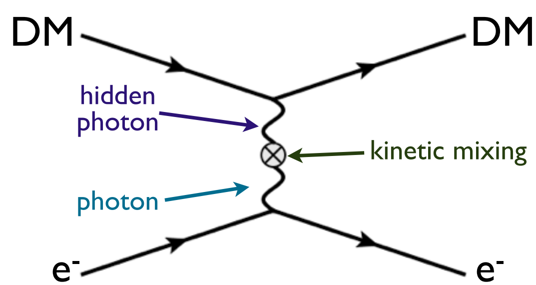


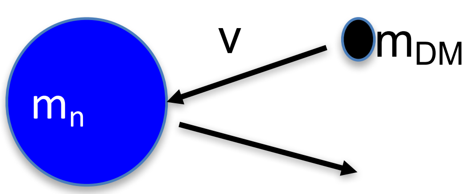
- Photon/Triplet Eximer Detector Sensitivity: ~ 18 eV /7
- Roton Detector Sensitivity: ~30 meV /7

3) 1MeV-300 MeV DM Searches with Electronic Recoils

- What can we say about DM with M_{DM} < 200 MeV
- 10 MeV DM nuclear recoils: <Er> ~ 3meV
- Dorenzo, Essig et al (1108.5383)



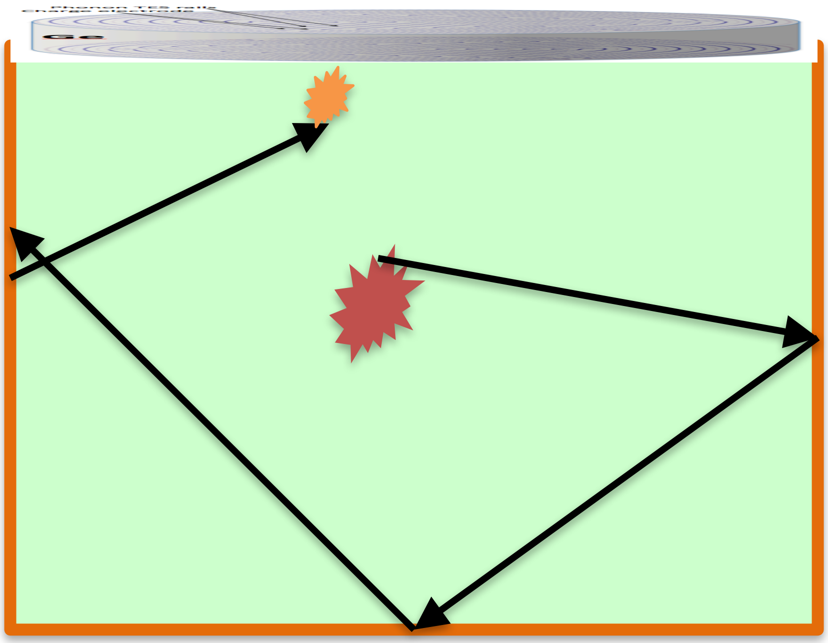




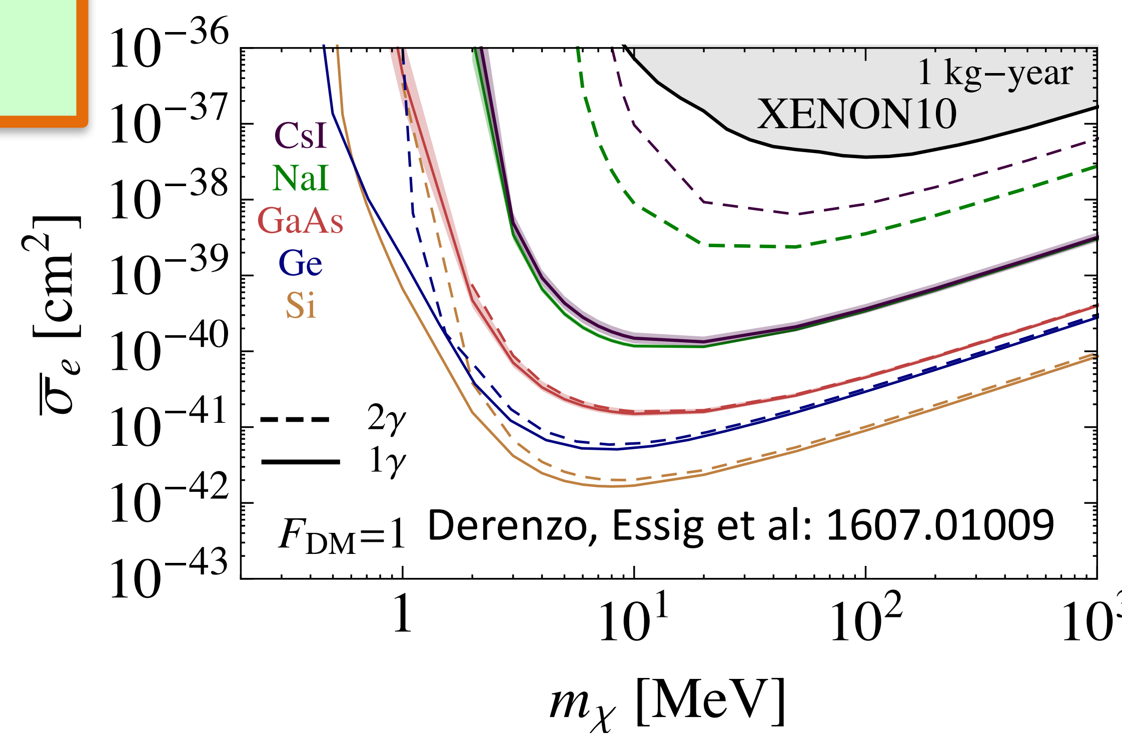
$$\Delta E = \frac{\Delta P^2}{2M_n} \lesssim \frac{2M_{DM}^2 v^2}{M_N}$$

For < 300 MeV Dark Matter don't pay the kinematic penalty. Search for elastic scatters between DM and e^-

ER DM Searches with Scintillators



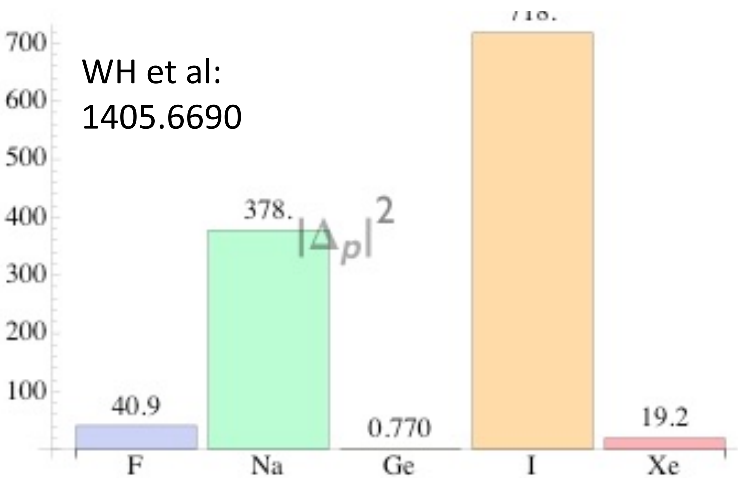
- Use a low bandgap scintillating crystal (GaAs, NaI) and couple to a single photon sensitive large area detector with no dark count rate
    - ~~PMT~~
- You pay a penalty compared to semiconductor detectors
- Different Systematics



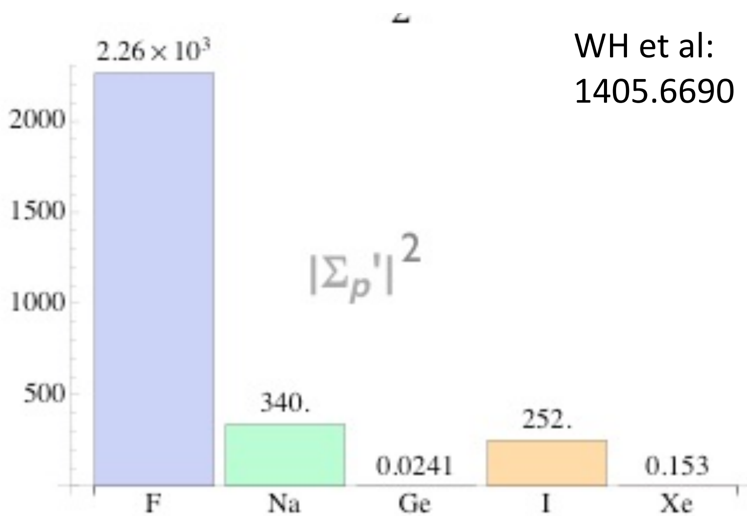
Photon Detector Sensitivity: 1.5 eV/ 7

4) Exotic Coupling High Mass Dark Matter

Orbital Angular Momentum Coupling



Vector (Transverse) Proton Spin Coupling

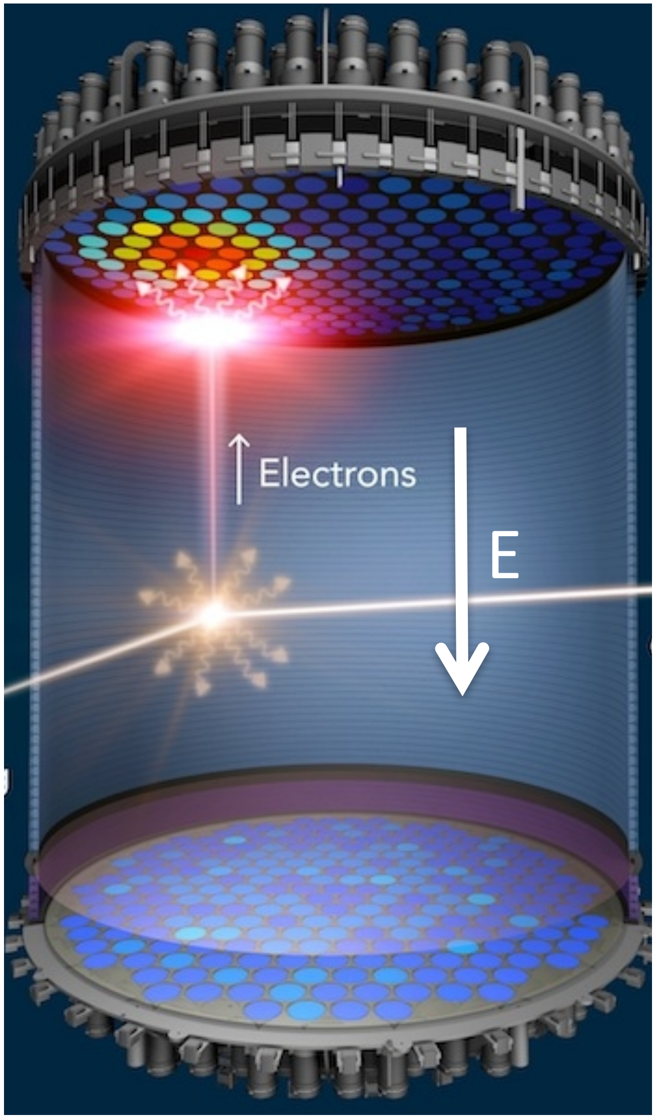


- Traditional ER/NR DM targets all [even, even] low angular momentum nuclei: Xe, Ar, Ge, Si
- What if DM couples via spin? What if DM coupling has strong velocity dependence (WH 1405.6690)?
- ~10 kg of Scintillation + Phonon Detectors for ER/NR rejection made from NaI and CaF_2 could compete with much larger experiments.
- Apples to apples test of DAMA
  - 1410.1573
  - 1603.02214
- Photon Detector:
  - ~2.5 eV/ 3 Sensitivity

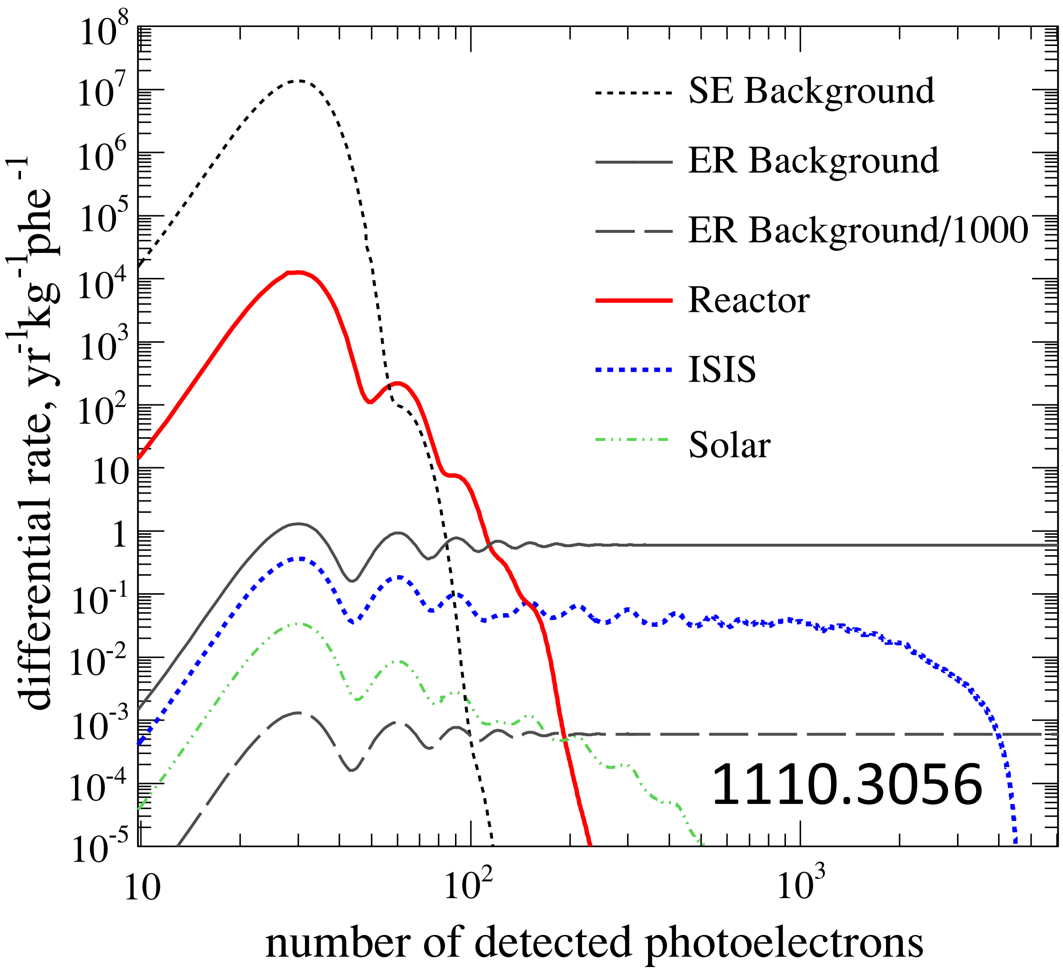
Science Requirement Summary: Photon/Roton Detector Sensitivity

	Sensitivity ($\boldsymbol{\sigma}$)	
0νDBD	10 eV	
He Scintillation	2 eV	
Exotic Coupling Dark Matter	0.75 eV (still good if higher)	
ER DM with GaAs	0.25 eV	
He Roton	5 meV	

Dark Counts



e$^-$ (S2) Background Rate in Zeplin III



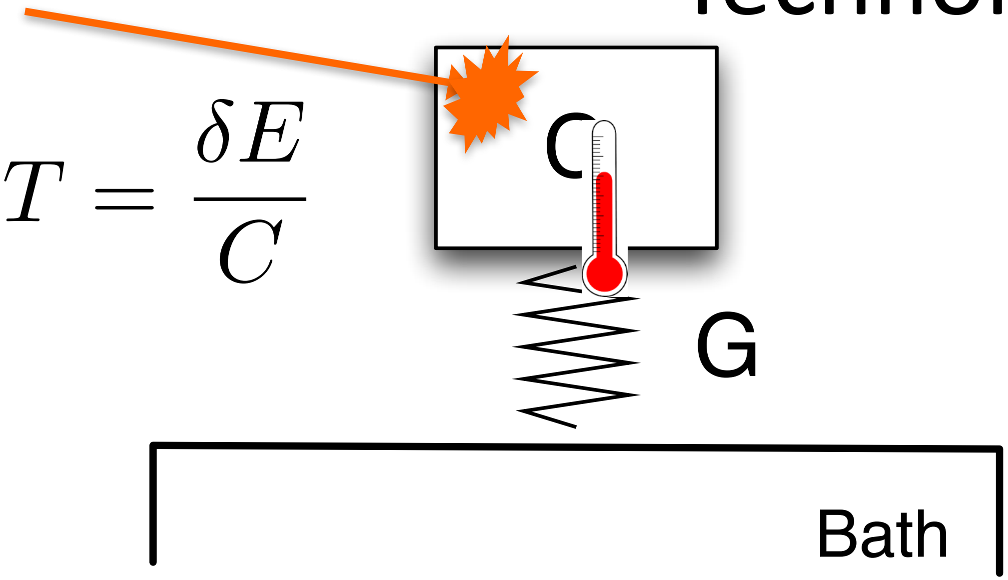
R_{1e-} = 5.7 Hz -> YIKES!

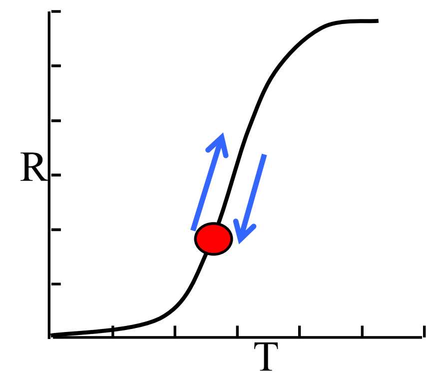
Science Requirement Summary: Photon/Roton Detector Dark Counts

	Sensitivity ($\boldsymbol{\sigma}$)	Dark Count
0νDBD	10 eV	Some Allowed
He Scintillation	2 eV	None
Exotic Coupling Dark Matter	0.75 eV (still good if higher)	Some Allowed
ER DM with GaAs	0.25 eV	None
He Roton	5 meV	None

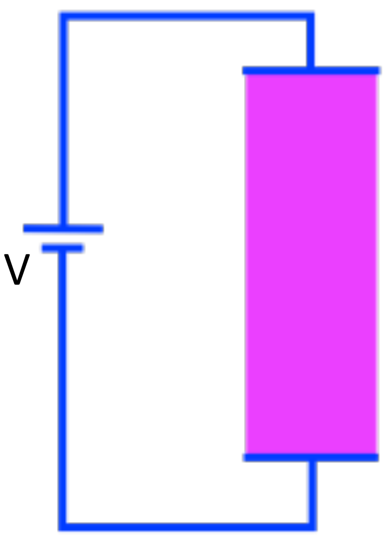
Low Temperature TES Calorimeter Technology

$$\delta T = \frac{\delta E}{C}$$





- Transition Edge Sensor (TES): A superconducting metal film (W) that is externally biased so as to be within its superconducting/normal transition
- **"Near Equilibrium Sensor": No Dark Count Rate**

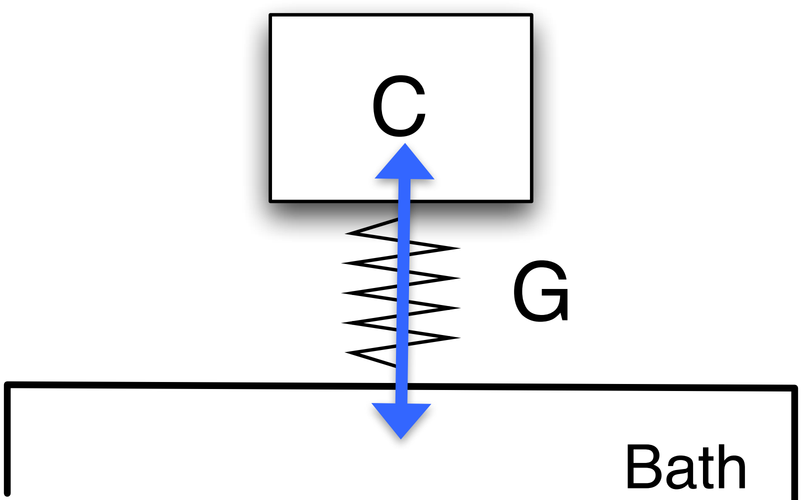


Calorimeter Sensitivity

$$\sigma^2_{<E>} = \sum_i (E_i - <E>)^2 \frac{e^{-\beta E_i}}{\sum_j e^{-\beta E_j}}$$

$$= \frac{\sum_i E_i^2 e^{-\beta E_i}}{\sum_j e^{-\beta E_j}} - <E>^2$$

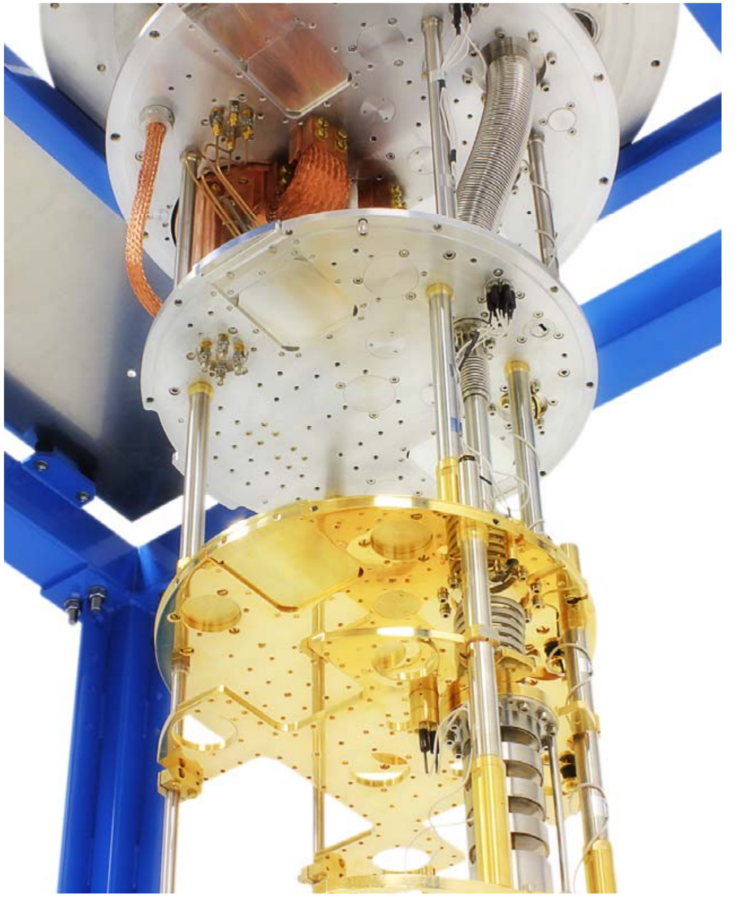
$$= -\frac{\partial <E>}{\partial \beta} = \frac{\partial <E>}{\partial T} k_b T^2 = C k_b T^2$$



~ Intrinsic Thermal Noise of Calorimeters

Calorimeter Optimization

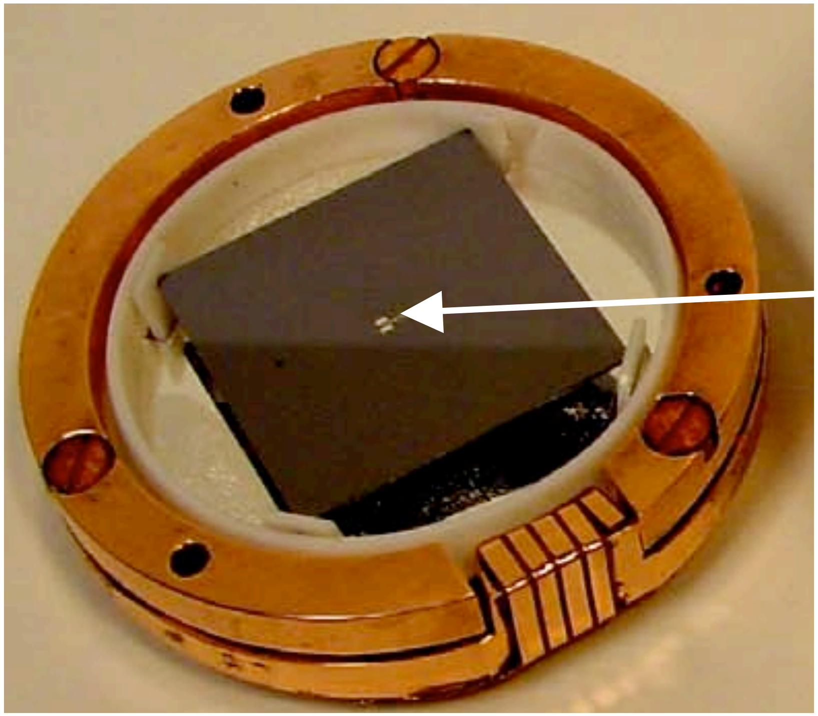
$$\sigma^2_{<E>} = C k_b T^2$$



- Minimize T
  - Dilution Refrigerators can cool detectors to 5mK
- Minimize C
  - ~~Small Volume~~
  - Low T
  - Insulators

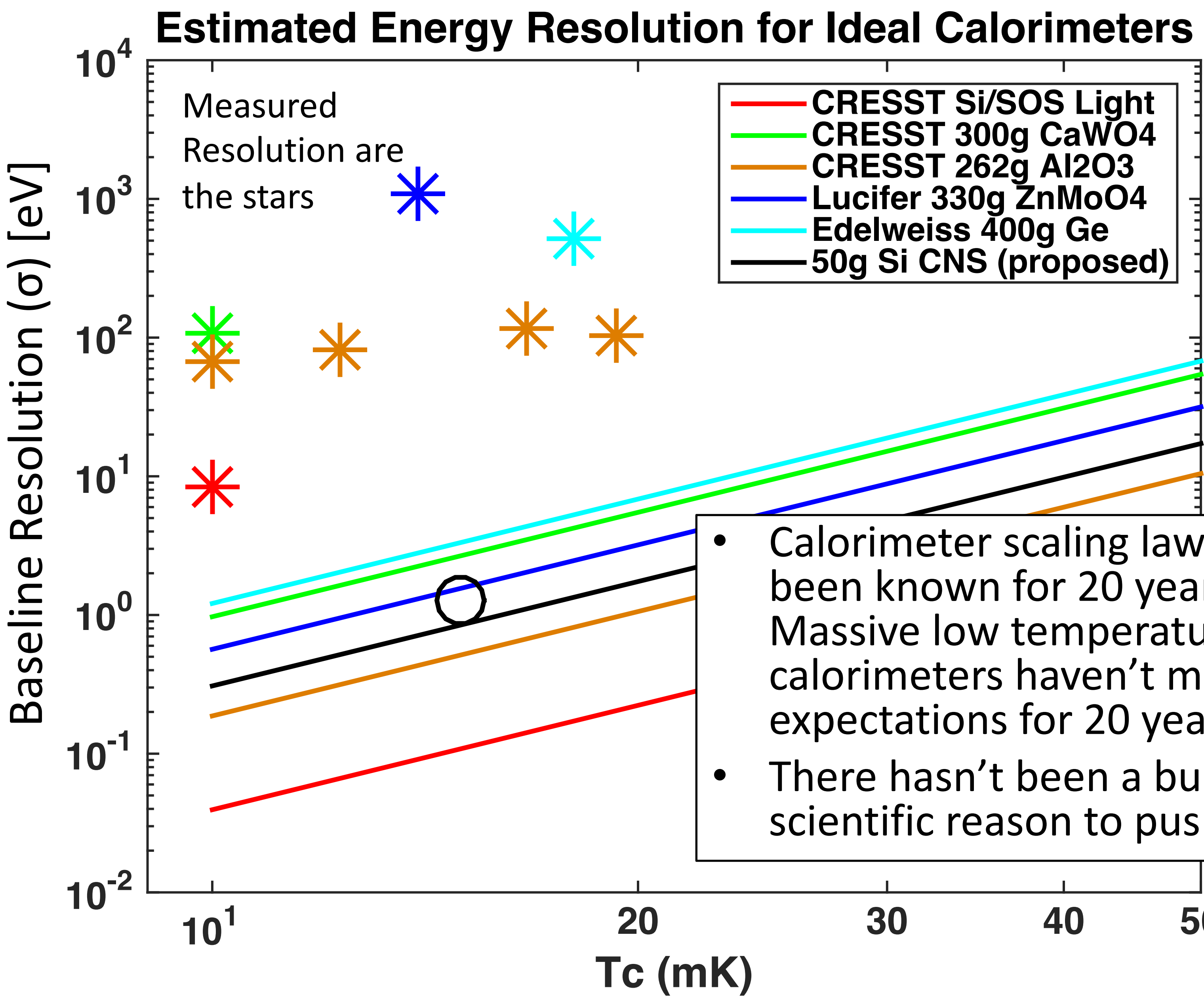
Freeze out

State of the Art: Thermal Cryogenic Photon Detectors



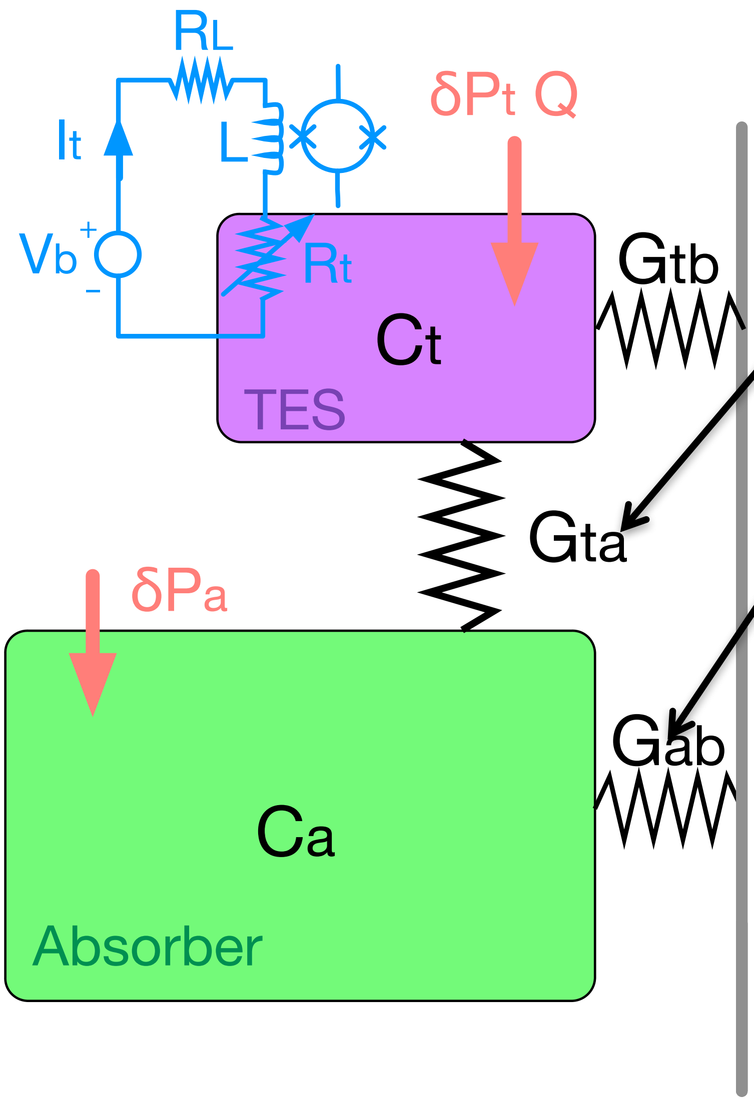
- CRESST Thermal Calorimeter Light Detector
  - (0809.1829)
  - 30mm x 30mm Si wafer
  - Single W TES (Tc ~10mK)
  - Sensitivity: 8.5 eV (σ baseline)

Shouldn’t this be a solved problem?



- Calorimeter scaling laws have been known for 20 years … Massive low temperature calorimeters haven’t met expectations for 20 years
- There hasn’t been a burning scientific reason to push

Culprit: Decoupling between the Sensor and Absorber at Low Temperature



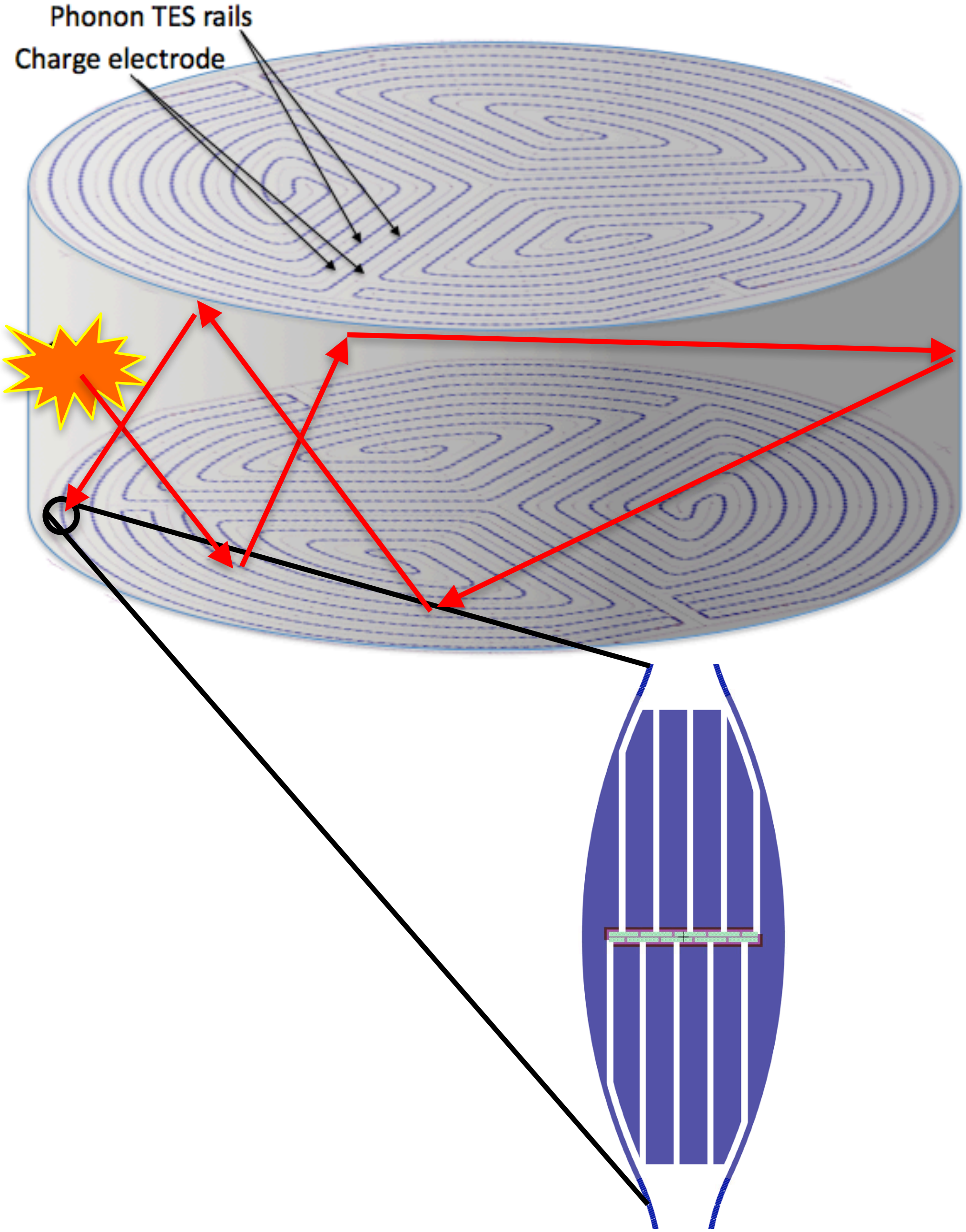
e-/phonon thermal conductance scales as T^4

Kapitza boundary conductance in the mechanical support scale as as T^3

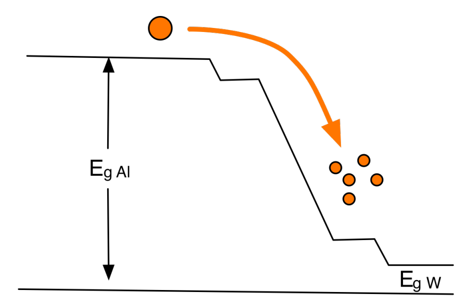
As T is decreased, it's harder and harder to keep the sensor:

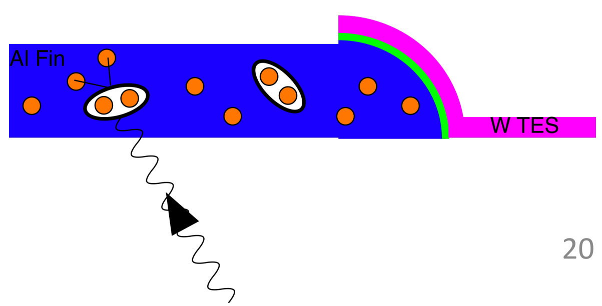
1. the sensor thermally coupled to the absorber
2. The absorber and sensor decoupled from the bath

Solution: Athermal Phonon Sensors

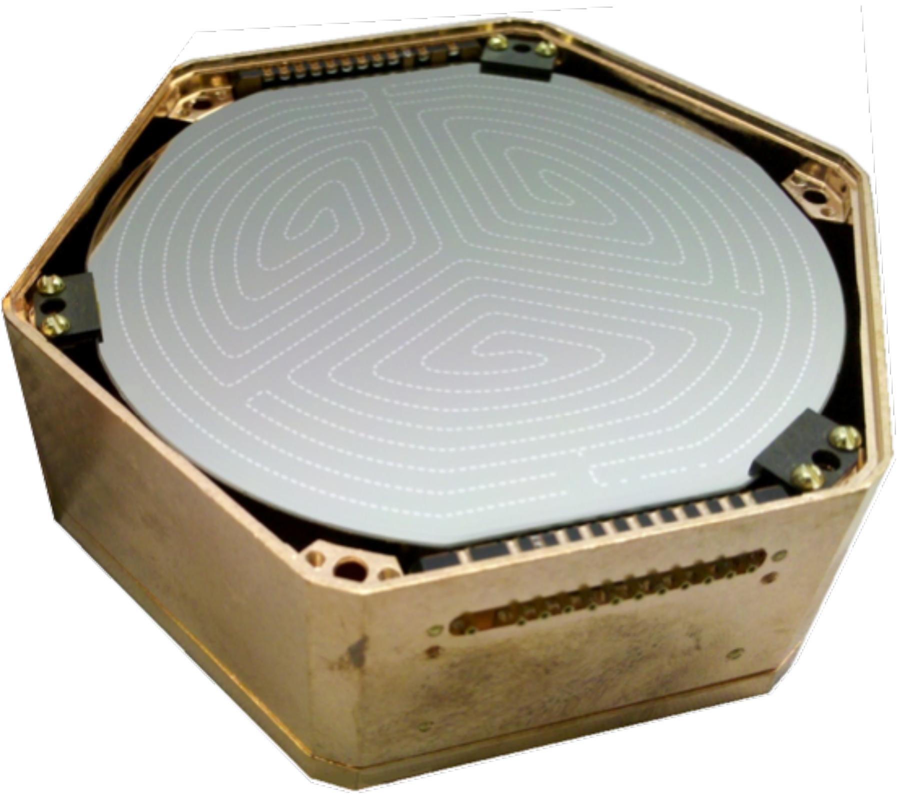


Collect and concentrate athermal phonon energy into TES via Al QP collection fins, completely bypassing the G_{ep} bottleneck



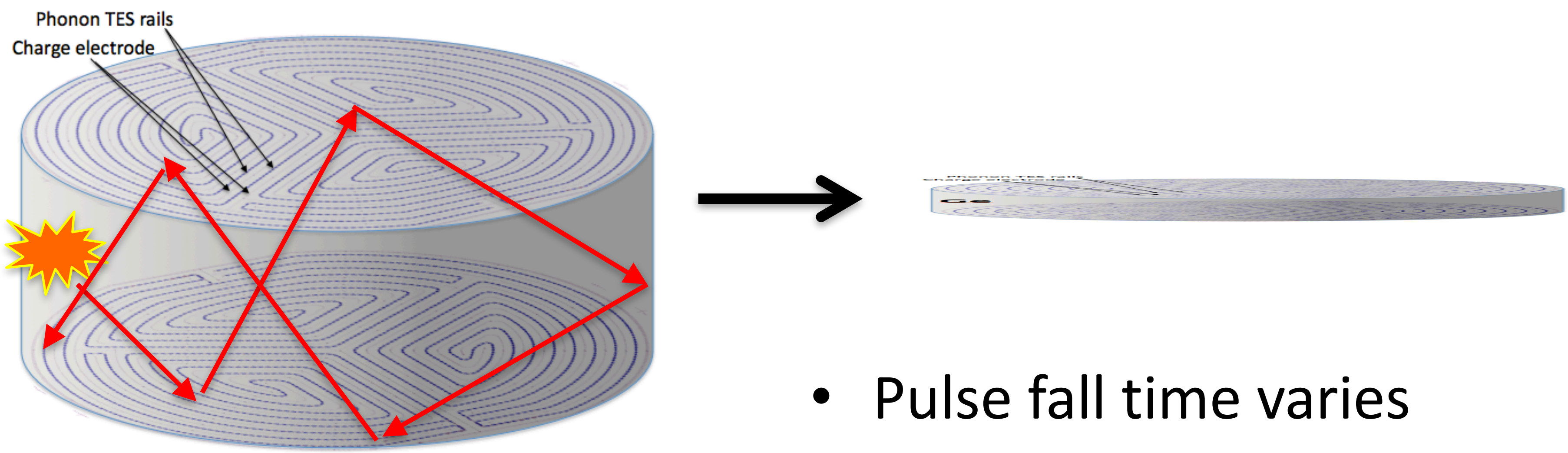


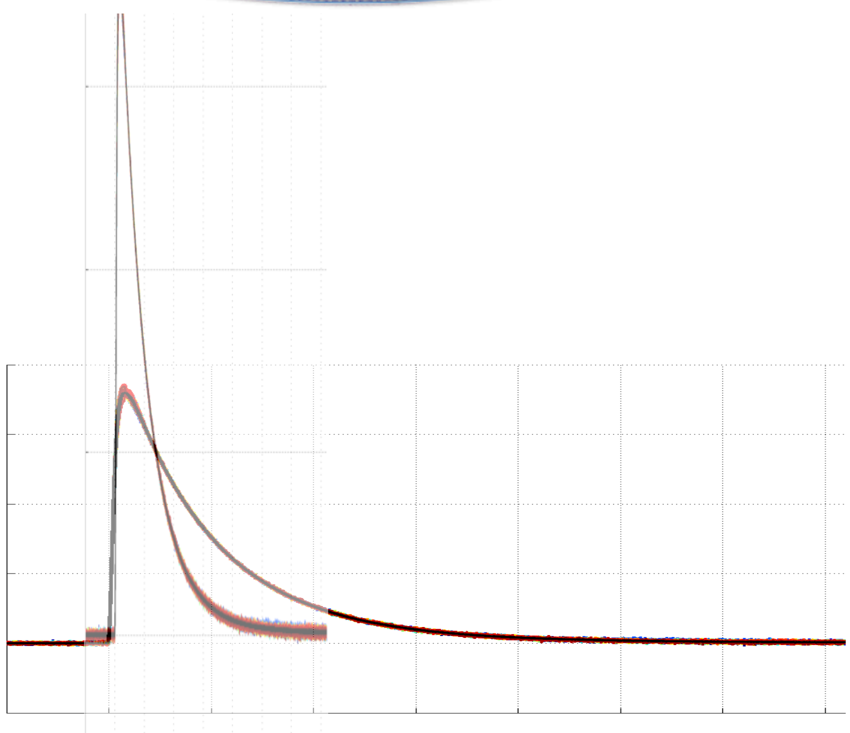
The Ultimate Cryogenic Photon and Roton Detector: thin / pixelized SuperCDMS Detector



STEAL FROM SUPERCDMS!

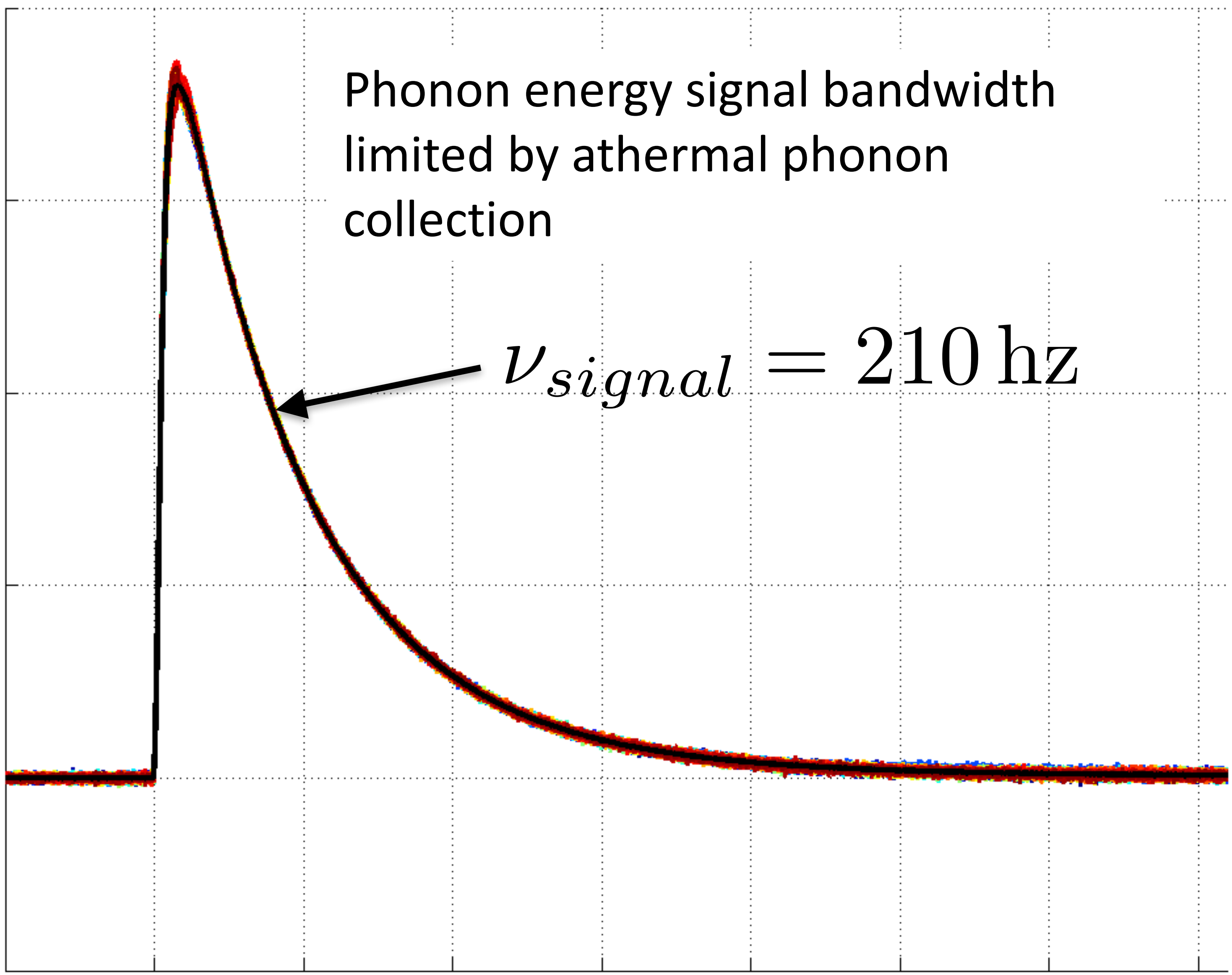
What happens when we shrink



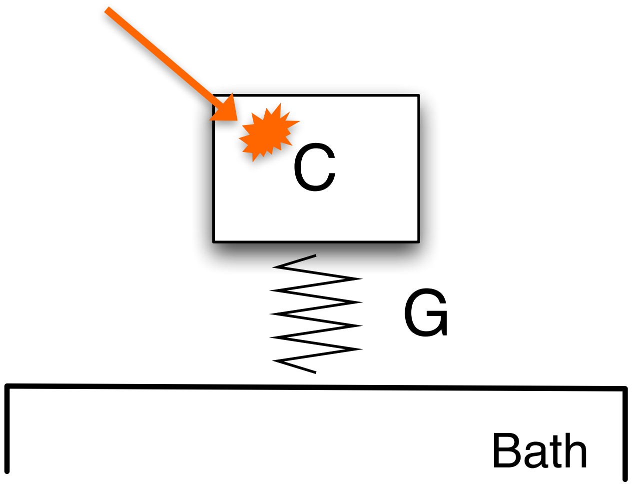


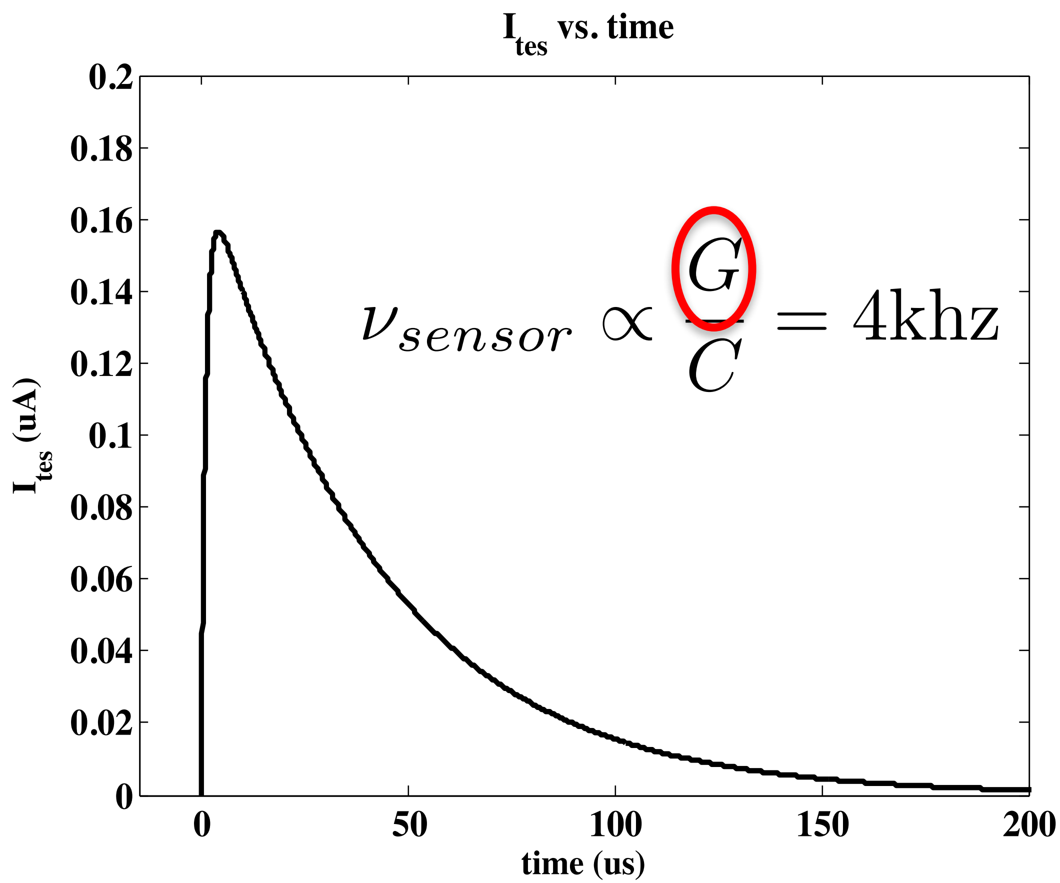
- Pulse fall time varies inversely with thickness!
- Phonon energy signal bandwidth limited by athermal phonon collection
- Energy Resolution scales as thickness$^{-1/2}$:
  - 25mm -> 1mm
  - 10 eV (HV Goal) -> 2 eV

Lowering T_c: Phonon Signal Bandwidth



Lowering T_c: TES Dynamics

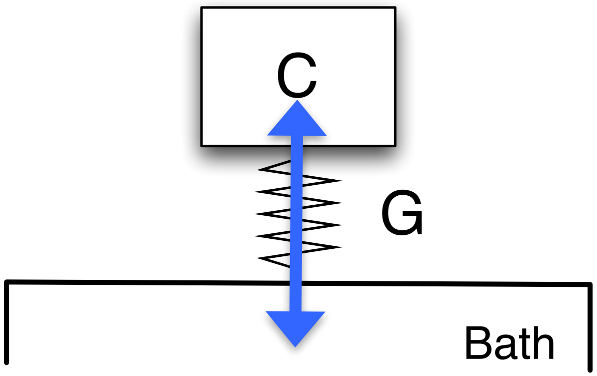




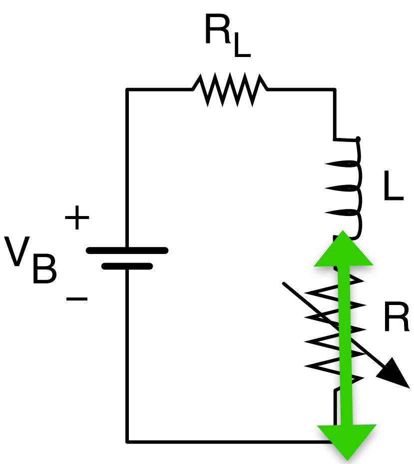
$$\nu_{sensor} \propto \frac{G}{C} = 4\text{khz}$$

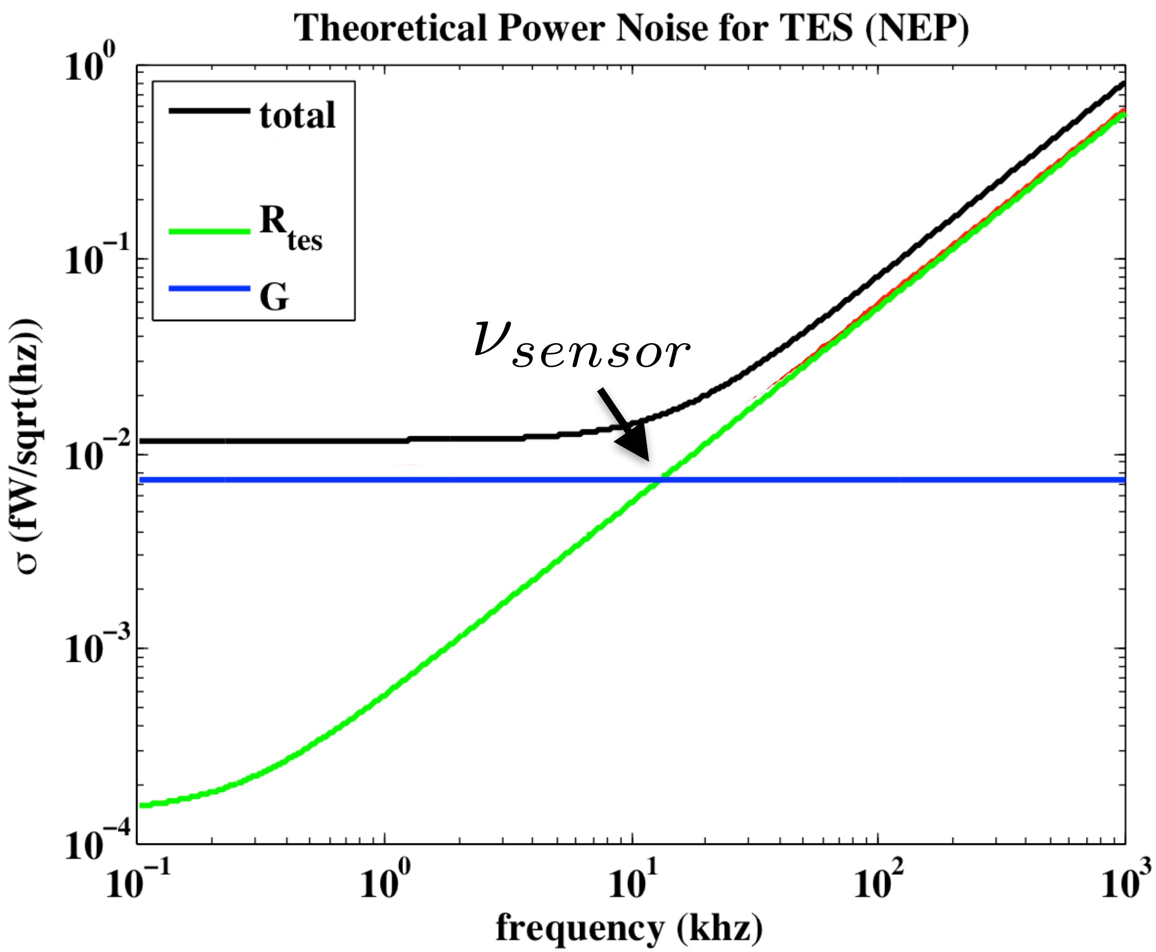
$$\nu_{signal} << \nu_{sensor}$$

Lowering T_c: TES Noise



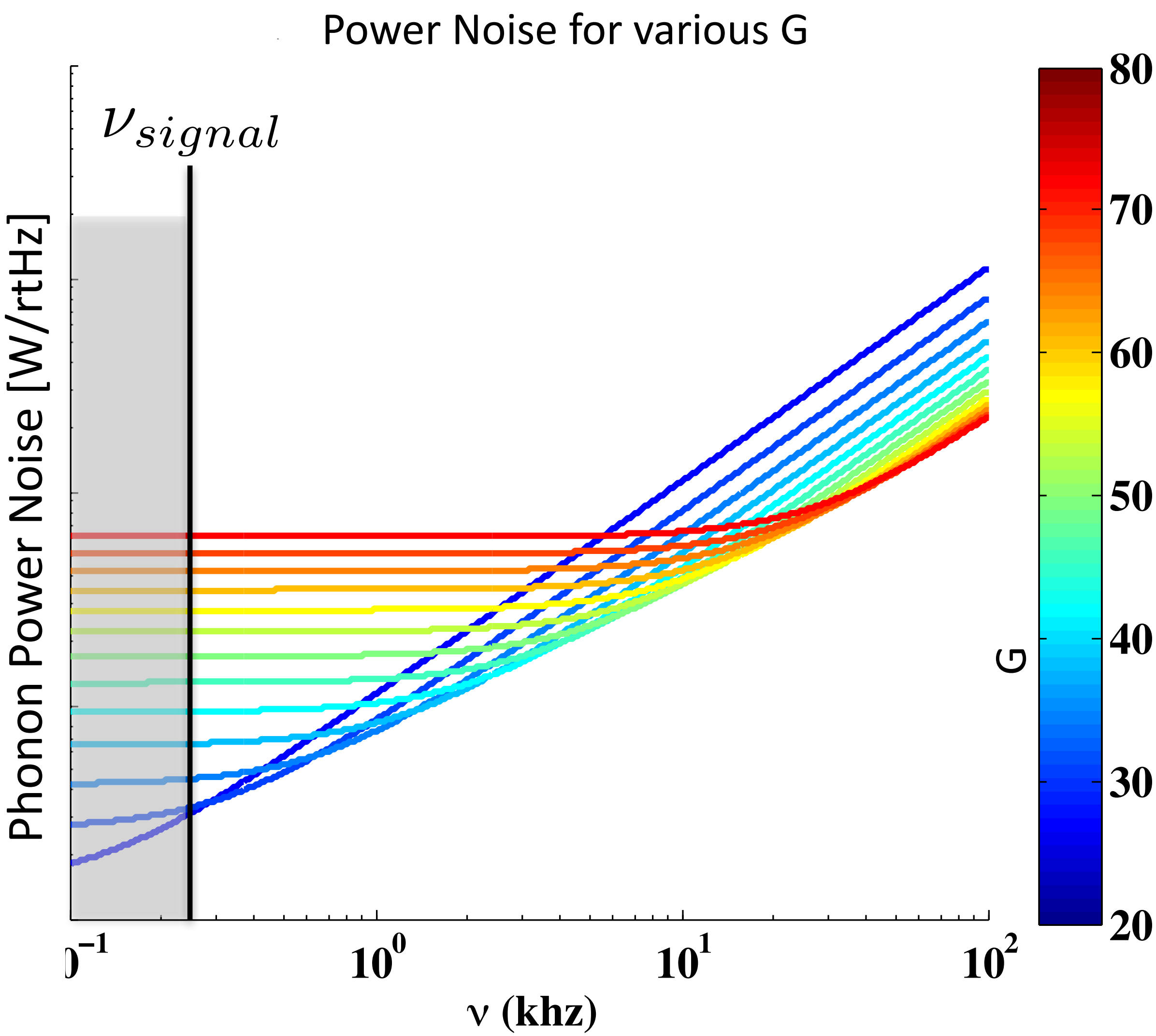
$S_{pG} = 4k_bT^2\mathbf{G}$





DC noise scales with G

Lowering T_c: Bandwidth Optimization Rule



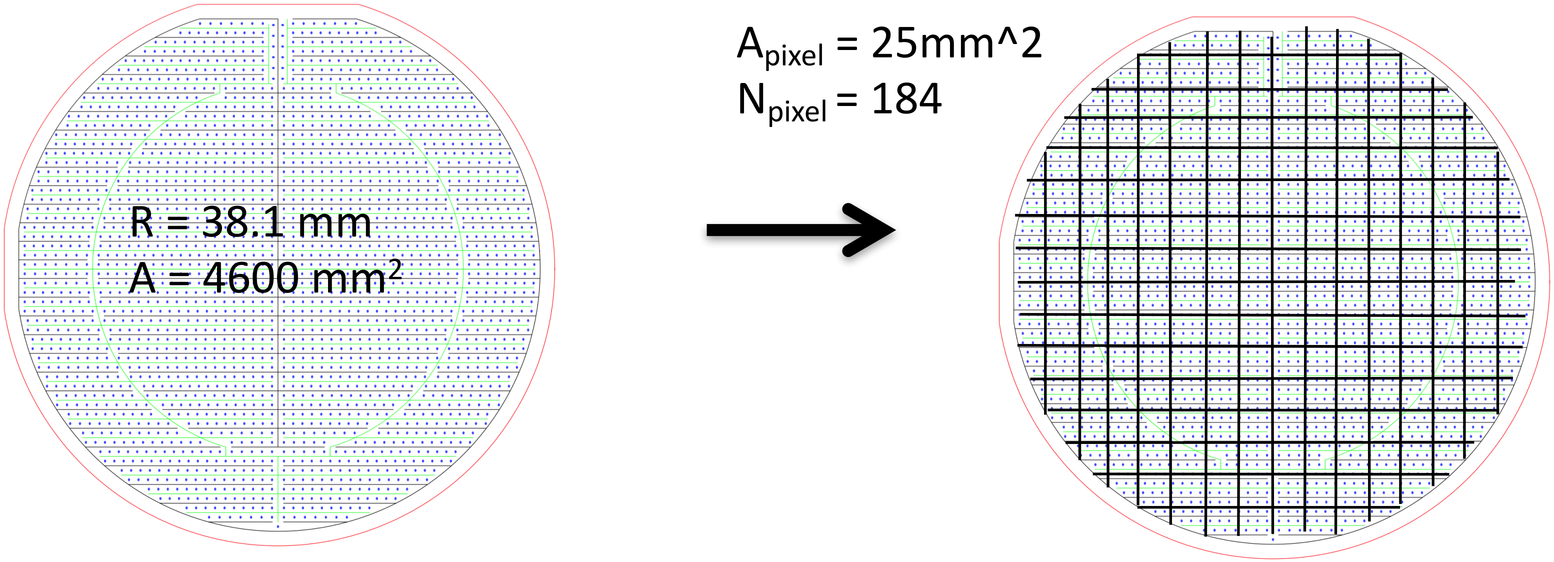
$$G \propto T_c^4$$
$$S_{ptfn} = 4k_b T_c^2 G$$
$$\propto T_c^6$$
$$\sigma_E \propto T_c^3$$

- Lower v_{sensor} (lower T_c) if $v_{\text{signal}} < v_{\text{sensor}}$
- Lower v_{signal} (decrease Al coverage) if $v_{\text{signal}} > v_{\text{sensor}}$

You can always say on T_c^3 scaling (in principle)

45mK-> 10mK: 2eV -> 20meV

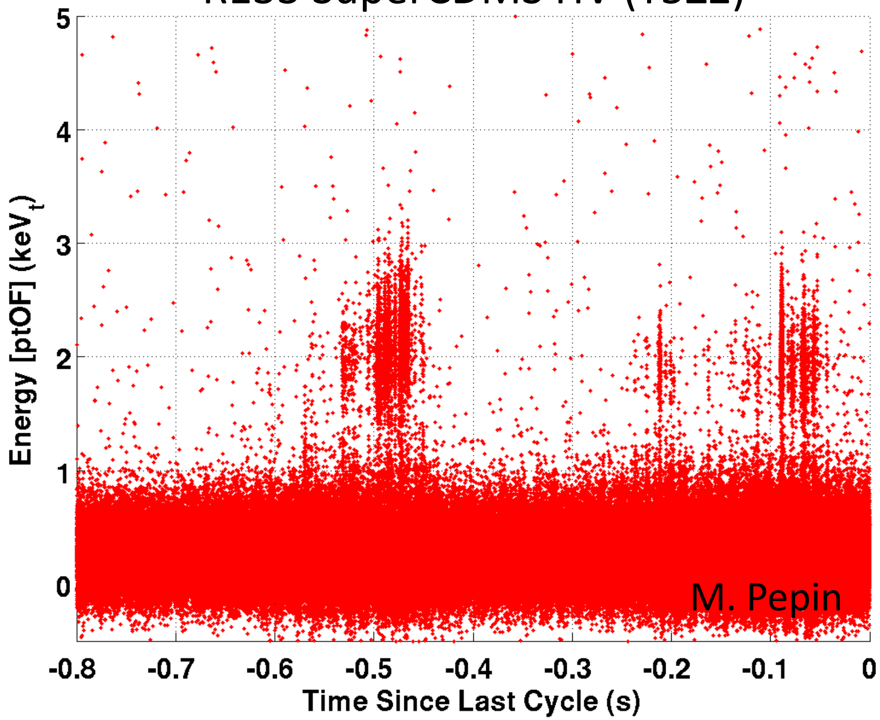
What happens when we pixelize?



- Naively, TES Noise sums in quadrature (Big Assumption!)
- 20 meV -> 1.5 meV

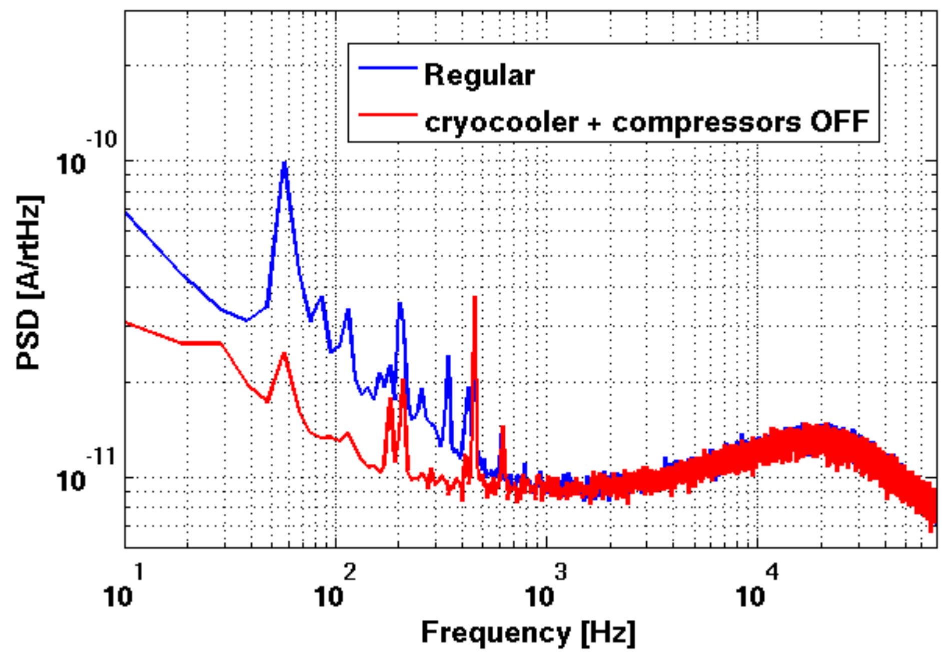
THE PROBLEMS

Problem #1: Vibrational Parasitic Power



Vibrations from the cryocooler produce high frequency phonons within our detectors which look like real events.

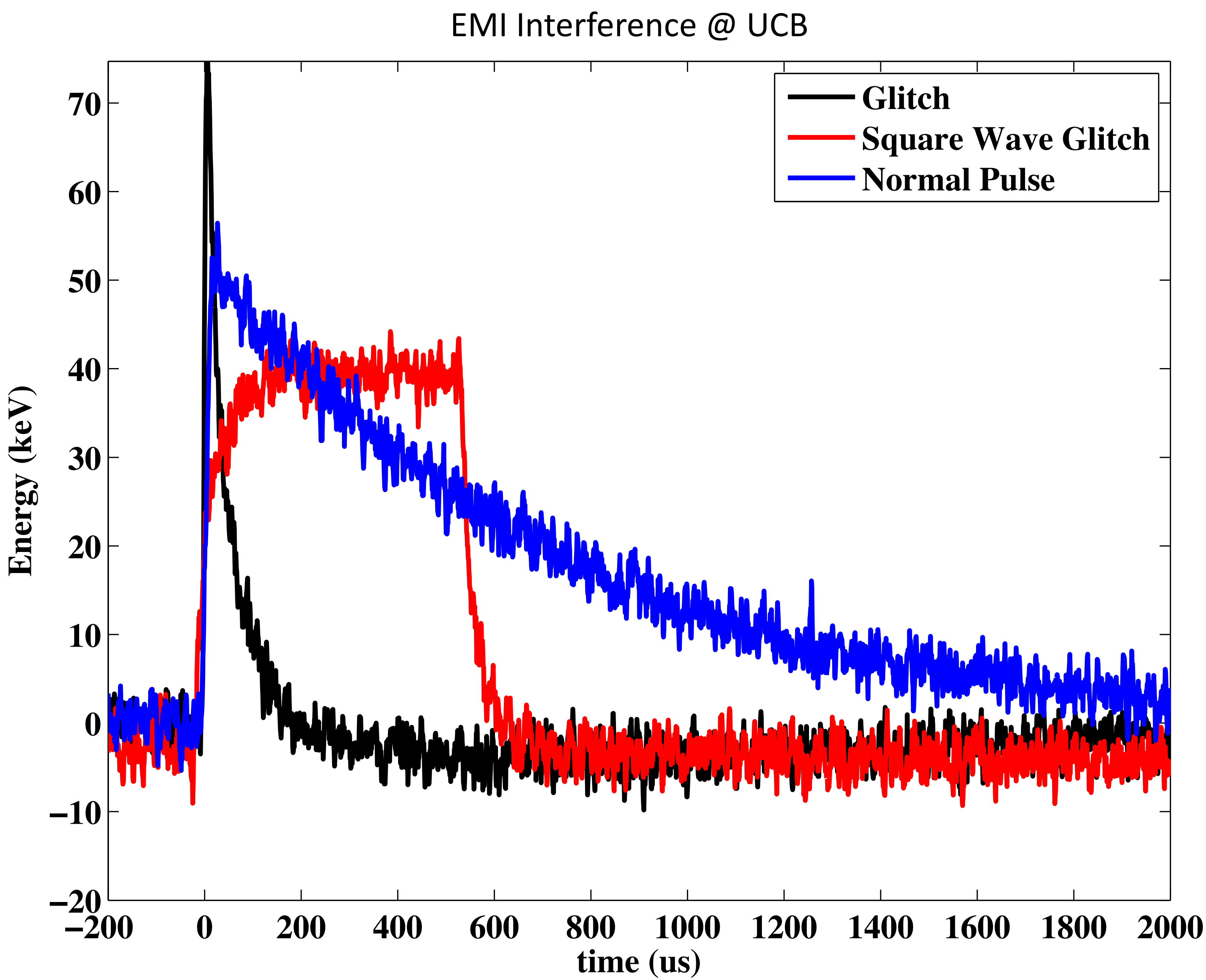
Baseline Noise PSD (T5Z2D)



Toggle CryoCooler ON/OFF

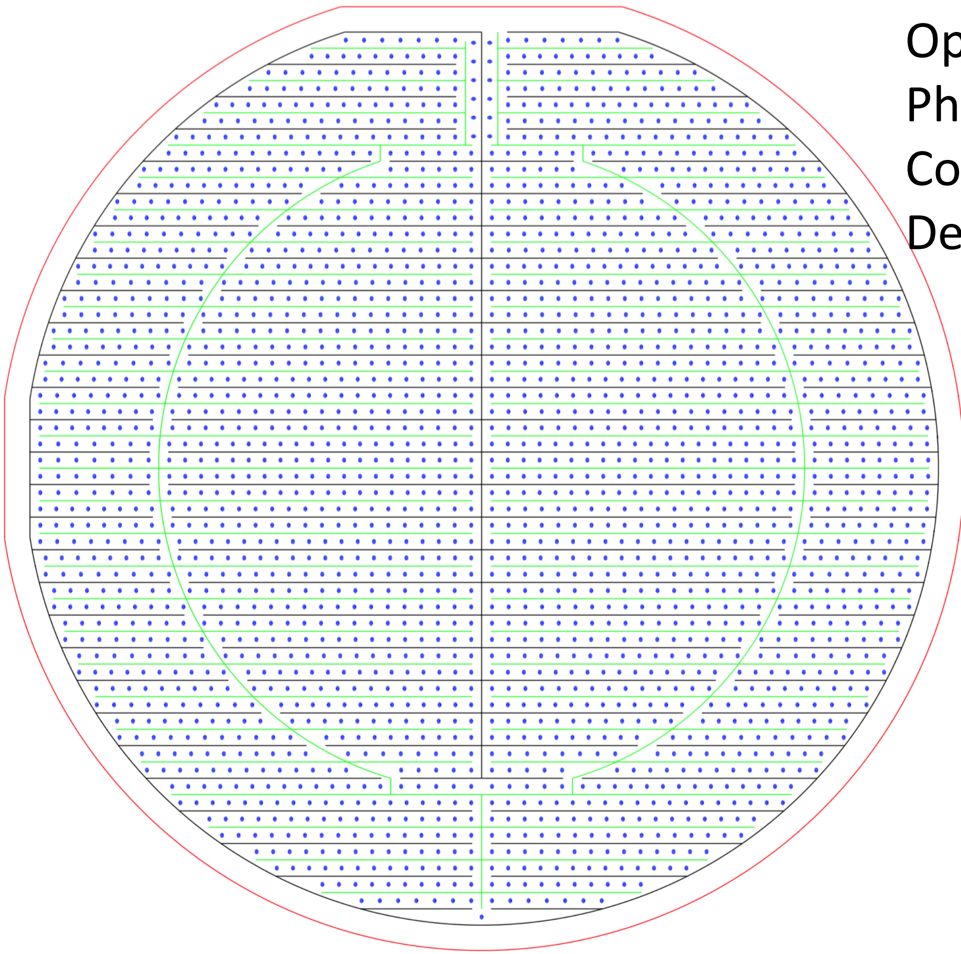
- Threshold: $12\sigma_{pt} \rightarrow 7\sigma_{pt}$ (?)
- σ_{pt}: 340eVt → 125eVt
- Caveats:
  - Study done at 0V
  - Trigger vs Analysis Threshold

Problem #2: RF Parasitic Power

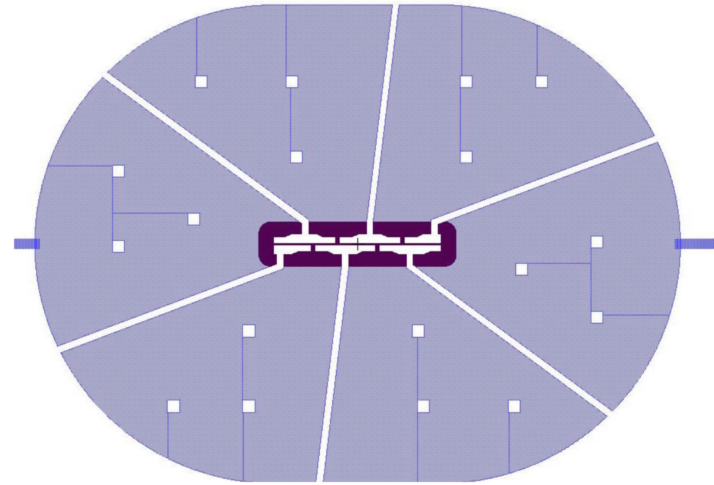


Current Progress

First Prototype Design



Optimized Phonon Collection Fin Design



Property	Value	Description
A_{Si}	45.6 cm^2	Absorber Area
M_{Si}	10.6 g	Absorber Mass
T_c	60mK	W TES Transition Temperature
T_{bath}	20mK	Bath Temperature
n_{tes}	1185	# of TES in parallel
h_{tes}	40nm	TES film thickness
l_{tes}	140 μm	TES length
w_{tes}	1.3 μm	TES width
$R_{o\,tes}$	100 mΩ	Operating Resistance
G	55 nW/K	Thermal Conductance
P_o	6.5 pW	TES Bias Power
$\sqrt{S_{p\,tfn}}$	$7.3\text{x}10^{-18} W/\sqrt{hz}$	Thermal Fluctuation Noise
C_{tes}	420 fJ/K	TES heat capacity
ω_{sensor}	4.12 kHz	sensor bandwidth
l_{fin}	200 μm	Al collection fin length
l_{diff}	340 μm	quasi-particle diffusion length
A_{fin}	16.2 x$10^4 \mu m^2$	collection fin area per TES
ϵ	48%	Phonon collection efficiency
$\omega_{collect}$	8.49 kHz	Phonon collection bandwidth
σ_p	2.2 eV	Estimated Phonon Resolution

Experimental Progress: 1st Run

- No source this run
  - no phonon collection efficiency measurement
- Did clamp kludge design work?
  - No vibrational sensitivity whatsoever. Unless the athermal phonon collection efficiency is truly horrid … solved
- Measured Phonon Sensor Parameters
  - T_c = 45mK: lowest ever measured -> beware of parasitic power
    - R_n = 150mOhm: Expected 300mOhm (TES width was 4um ☹)
    - T_{bath} = 37mK
    - P_o = 2pW
    - $S_p(0) = 1.75\times10^{-17}\ W/\sqrt{Hz}$: x3 higher than expected ☹
  - β ~ 0 : Evidence that β is getting smaller as we drop T_c?
  - τ_{eff} =119us: Suppressed by low R_o and T_{bath}
    - Estimated 25us falltime in perfect setup (too good to be true?)

Experimental Progress: Biggest 1st Run Mystery

- Phonon Pulse falltime:
  - Measured: 200us
  - Expected: 20us
- Huge Discrepancy!
- Hypotheses:

1. Just saturation effects (calibration source)
2. The Si surface was really rough due to overetching the aSi layer … could phonons really be bouncing around for that long?

2^{nd} Run Cooling Today

- No aSi layer
- Am Calibation source (2 Hz)

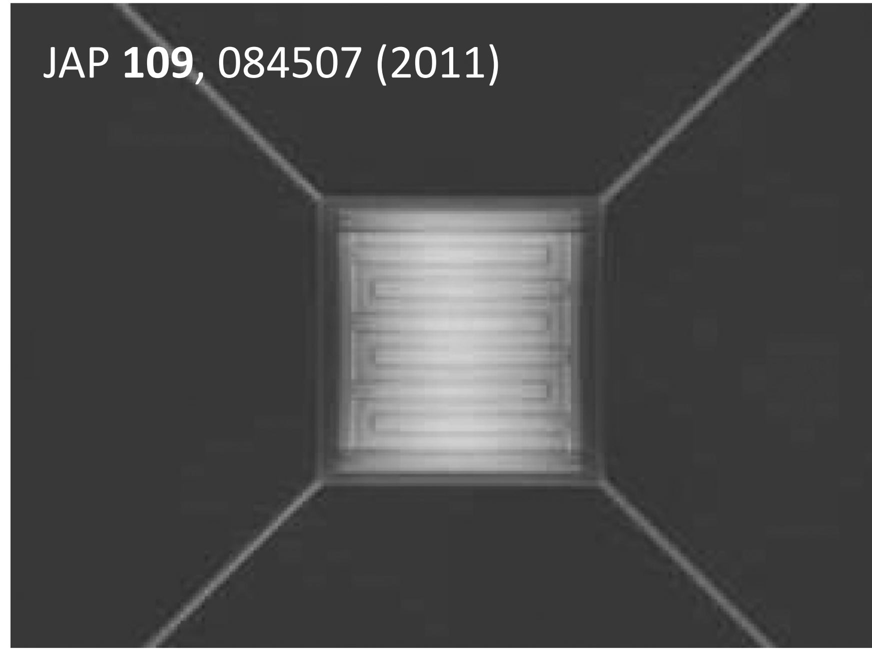
Summary

- A daunting, but theoretically possible path to meV scale devices
- At every stage in sensitivity development there are scientifically interesting uses

Backup

Resolution Limits: Parasitic Power

SAFARI has created devices with x75 smaller G & x9 smaller P_{bias} than we require



	SuperCDMS (modeled)	SAFARI (measured)
Tc	30 mK	111 mK
G	12800 fW/K	170 fW/K
P_{bias}	76 fW	8.9 fW
S_{NEP}	6×10^{-19} W/rthz	4.2×10^{-19} W/rthz

We're far from the fundamental limits on phonon resolution due to parasitic power